REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
29-10-2007

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
1 Nov 2004 – 27 Apr 2007

4. TITLE AND SUBTITLE
Computational Electromagnetics

5a. CONTRACT NUMBER
FA9550-05-1-0019

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Reitich, Fernando L.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Minnesota
School of Mathematics
206 Church St. S.E.
Minneapolis, MN 55455

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Dr. Arje Nachman /NE
Air Force Office of Scientific Research
875 North Randolph St., Rm 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR/NE

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
DISTRIBUTION A. Approved for public release; distribution unlimited.

AFRL-SR-AR-TR-07-0470

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Progress in the development of fast, error-controllable algorithms for the simulation of electromagnetic scattering throughout the frequency spectrum is reported. Advances are described in the development of (1) accelerated, high-order methods for the solution of general, penetrable scattering problems in the low-to-moderate frequency regime; (2) spectral methods for the solution of approximate high-frequency models (geometrical optics −GO−); and (3) general error-controllable high-frequency scattering solvers. Major accomplishments include the completion of work on (1) in relation with scalar scattering models and the extension of the algorithms to vector models and composite backgrounds; the design, implementation and refinement of a spectral/discontinuous Galerkin method to resolve the GO model in phase space; the advancement of a spectral inverse ray-tracing approach; the development of methods for the evaluation of high-frequency scattering off composite rough surfaces; the derivation of general high-frequency scattering solvers applicable to both single- and multiple-scattering configurations consisting of bounded obstacles in two and three dimensions; and the analysis and implementation of strategies to account for and accelerate the evaluation of multiple-scattering effects.

15. SUBJECT TERMS
Computational electromagnetics, high-frequency scattering, high-order numerical methods, fast algorithms, error control

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	U		**19b. TELEPONE NUMBER** (*Include area code*)
U	U	U			

Computational Electromagnetics
AFOSR Contract #FA9550-05-1-0019

Final Progress Report

1 November 04 - 27 April 07

PRINCIPAL INVESTIGATOR:

Fernando Reitich
School of Mathematics
University of Minnesota
127 Vincent Hall
206 Church St. S.E.
Minneapolis, MN 55455
Phone: (612) 626-1324
Fax: (612) 626-2017
reitich@math.umn.edu

CO-PIs/SUBCONTRACTORS:

None

OBJECTIVES

The objective of the effort sponsored by the present contract consisted of the development of fast and accurate algorithms for the evaluation of electromagnetic scattering for frequencies throughout the electromagnetic spectrum. To this end, a central focus of the research related to the development of new high-order integral equation methods that would allow for accurate and efficient approximations of full-wave solutions in high-frequency applications. The novel algorithms that we have thus developed under the sponsorship of AFOSR can, in fact, be thought of as providing a means to rigorously connect numerical approximations from very low to very high frequencies. Indeed, at the lower end, the resulting approach possesses the desirable characteristic that it seamlessly reduces to any standard integral equation solver as the frequency decreases. Moreover, at the other extreme, the procedure is based on the use of a geometrical optics (GO) ansatz (or of the related physical optics or geometrical theory of diffraction approximations) for the unknown surface currents and, thus, it naturally couples to classical approximate high-frequency solvers. As a result, advances in the development of fast and accurate algorithms that are applicable at each end of the spectrum also impact the performance of the overall infrastructure and they therefore also constituted a subject of concurrent research. In more detail, specific objectives included:

(1) the development of a fast and high-order method for the solution of general, penetrable scattering problems in the low-to-moderate frequency regime. Advances in this area were based on the design of a methodology that allows for the numerical approximation of the solution of the relevant (volumetric) integral-equation formulation with tunable convergence orders while retaining a computational cost that grows nearly linearly with the number of unknowns. The approach relies on the integration of accurate schemes for the treatment of (thin volumes near) material interfaces with efficient FFT-based techniques for the evaluation of the interaction between degrees of freedom away from these.

(2) the development of high-order methods for the solution of approximate high-frequency models. Work in this connection concentrated on the design of effective approximation strategies for the GO solution that rely on Eulerian discretizations in phase-space, and on the development of spectrally accurate (inverse) ray tracing schemes in the physical domain. For the former, emphasis was placed on the development of techniques that can accurately handle material interfaces (to retain accuracy) and that capitalize on the smoothness of solutions in phase-space (which enables the use of rapidly convergent approximations). In connection with ray tracing, our effort focused on the implementation of novel spectral procedures for two- and three-dimensional calculations.

(3) the development of general error-controllable high-frequency scattering solvers. The rather ambitious objective of this program was to derive numerical approximation techniques that allow for the prediction of electromagnetic signatures at arbitrarily large frequencies with prescribed accuracy and using discretizations that are *independent* of frequency, that is, without having to resolve on the scale of a wavelength. In other words, the objective here was to produce an algorithm that displays the advantageous properties (frequency-independent discretizations) of GO solvers (e.g. such as those related to **(2)** above) while retaining the most desirable characteristics (error-controllability) of rigorous methods (cf. **(1)**).

STATUS OF EFFORT

Referring to the numbering above, accomplishments include:

(1) the development of both two- and (scalar) three-dimensional versions of the integral-equation-based penetrable scattering solvers. As we mentioned, the schemes rely on a separate treatment of "thin volumes" near material interfaces and "bulk volumes" away from these. For the former, high-order accuracy is attained using high-order quadratures based on suitable changes of variables to account for the (singular) interaction between "adjacent" (i.e. nearby) degrees of freedom; (regular) non-adjacent interactions, on the other hand, are computed efficiently through the use of "equivalent sources" on Cartesian grids and FFTs. Parallel implementations were also realized, as the separation into adjacent and non-adjacent interactions is naturally amenable to parallel calculations, with local interactions concurrently evaluated and with long-range effects accounted for with standard parallel FFT codes. The bulk, volumes, on the other hand, are easier to handle as their smoothly varying optical properties allow for the use of spectral methodologies, again based on FFTs (though care must, of course, be exercised in the discretization of the singular integrals). Finally, the use of Fourier transforms on Cartesian grids further enables the rapid evaluation of the cross interaction between thin and bulk volumes (see Appendix A). *[Work with graduate student A. Anand — not supported by this contract].* In addition to these advances we have further attained initial implementations of extensions to three-dimensional vector scattering and composite (e.g. stratified) models which include, in the latter case, efficient evaluation mechanisms for the appropriate Green function. *[Work with graduate student Jiaqi Yang — supported by this contract].*

(2) the design of schemes of arbitrarily high-order accuracy for two- and three-dimensional evaluations of GO solutions. These include approximation procedures for solutions defined in both physical and extended "phase space". The former rely on a spectral (inverse) ray tracing algorithm (localized, in three dimensions), while the latter is based on Fourier expansions in the phase variables and on discontinuous Galerkin (DG) approximations of the resulting (hyperbolic) system for the Fourier coefficients. In connection with the phase space solutions, a nearly optimal implementation for cylindrical geometries was attained which includes: (i) the ability to work with general unstructured meshes; (ii) the use of Galerkin bases on these constructed from Jacobi polynomial with natural orthogonality characteristics, and of specialized quadratures that enable arbitrarily accurate integration; (iii) the employment of sparse matrix storage/multiplication to allow for rapid evaluations; (iv) the incorporation of isoparametric elements which, as we have shown, avoid the spurious oscillations that arise on the use of polygonal/polyhedral boundary approximations and thus allow for the retainment of high-order accuracy in the presence of curved reflecting boundaries; and (v) the integration of (p-) adaptivity strategies that significantly improve on the efficiency of the overall approach (see Appendix A).. *[Work with postdoctoral associates J. Qian, J. Wang and C.-Y. Kao and Prof. B. Cockburn — not supported by this contract]*. As for the *spectral* GO solver in physical space, we have also completed initial implementations for *general* two- and three-dimensional geometries. A significant challenge in this connection related to the accurate evaluation of (singular) reflected fronts that do not illuminate the entire scatterer; following our overall philosophy, our solution strategy is based the use of appropriate cut-off functions and spectral interpolations in parametric space. *[Work with graduate student A. Anand — not supported by this contract]*.

(3) significant advances in the design and implementation of new schemes for the simulation of **(i)** three-dimensional rough-surface scattering at high-frequencies that greatly improves on the classical Kirchhoff approximation (KA), at a very modest additional cost; and **(ii)** high-frequency scattering from cylindrical, and general bounded three-dimensional geometries that rigorously accounts for every effect, including shadowing and multiple scattering. As we further explain below, in connection with the solvers corresponding to **(i)** above, a focus over the course of this contract related to the implementation of (integral-equation) schemes based on high-order expansions of surface currents in inverse powers of the wavenumber for the solution of the full Maxwell equations in three space dimensions, and the incorporation of these methods into a new, high-order strategy for the solution of scattering problems off multi-scale surfaces *[work with graduate student C. Turc — not supported by this contract]*. In addition, significant advances were made, specifically in connection with the evaluation of the relevant (quasi-periodic) Green function, towards a more general rough-surface scattering solver that incorporates some of the ideas developed in connection with **(ii),** to deliver a spectrally accurate algorithm that allows for frequency-independent discretizations *[work with graduate student H. Kurkcu — supported by this contract]*. In connection with high-frequency techniques for bounded-obstacle scattering applications, our effort was largely devoted to the development of algorithms applicable to cylindrical geometries and to their extension to allow for the treatment of general three-dimensional configurations. The resulting implementations include: (a) an integration with GO solvers to garner phase information for the unknown surface currents; (b) a suitable localization procedure to enable approximate quadratures with a frequency-independent computational cost; (c) an accurate treatment of shadowing transitions through their exact resolution; and (d) the incorporation of an iterative procedure to account for multiple scattering (see Appendix A). Due to its significance in general scattering calculations, substantial additional effort was devoted to the latter issue of multiple scattering effects, which resulted in: (i) a rigorous analysis of the convergence of multiple scattering iterations for interacting two- and three-dimensional surfaces, and its use in the development of strategies that accelerate their convergence *[work with graduate student F. Ecevit — supported by this contract]*; (ii) the development of preconditioning techniques based on an "iterated KA", and the implementation of schemes to further accelerate the convergence of the iterations (via more sophisticated schemes for the solution of linear systems, such as ORTHODIR, GMRES, etc), *[work with post-doctoral associate Y. Boubendir — not supported by this contract]*; and (iii) the design of an alternative strategy to account for multiple reflections that allows for their simultaneous (rather than iterative) determination *[work with Prof. O. Bruno — not supported by this contract]*.

ACCOMPLISHMENTS/NEW FINDINGS

As mentioned above, our work in computational electromagnetics has advanced on several fronts, with an overall goal of developing efficient and accurate algorithms for the simulation of scattering processes throughout the electromagnetic spectrum. To this end, our program has been closely coordinated with that of Dr. Bruno at Caltech (who will be reporting separately). As a general guideline, we have followed a path of designing the different components of a general computational suite in a way so that the components are themselves of intrinsic and immediate interest and applicability.

Examples of such components are those described in **(1)** and **(2)** above, dealing with high-order integral-equation solvers for low-to-moderate frequencies, and high-order spectral/finite-element schemes for the solution of approximate high-frequency models. In connection with the former, as we said, we have concentrated on the attainment of penetrable-scattering solvers that allow for a high-order accurate treatment of scalar and vector models in possibly complex backgrounds. These developments are being coordinated so as to be applicable to the evaluation of electromagnetic scattering while, at the same time, allowing for their use in the simulation of other wave phenomena (e.g. elastic wave propagation). The latter use is serving the dual purpose of providing an opportunity for technology transfer and of enabling experimental validations for the resulting codes. These opportunities are being pursued in two concurrent collaborative projects with scientists at Schlumberger-Doll Research (SDR) on geophysical prospection and at the Ultrasound Research Laboratory at the Mayo Clinic (Rochester, Minnesota) in the context of numerical modeling of vibro-acoustography (UVA). Our collaboration with SDR has produced an efficient fully three-dimensional integral-equation solver for (elastic) wave scattering off inhomogeneous media that is based on a stress-velocity formulation, and which incorporates acceleration and preconditioning schemes largely inspired by the work sponsored by the present contract. In relation with work on UVA, on the other hand, our efforts to date have resulted in a preliminary simulation framework (initially, for p-wave propagation) that is based on the solution of integral equations, and alternatives based on hybrid combinations with asymptotic numerical models (e.g. parabolic approximations). As we said, the numerical approach relies on extensions of our previously designed algorithms, and it can account for the complete experimental setup (i.e. the −high-frequency− wave generation at the transducer, the propagation to the specimen, its localized −nonlinear− excitation and the −low frequency− returns to the hydrophone); see Figure 1.

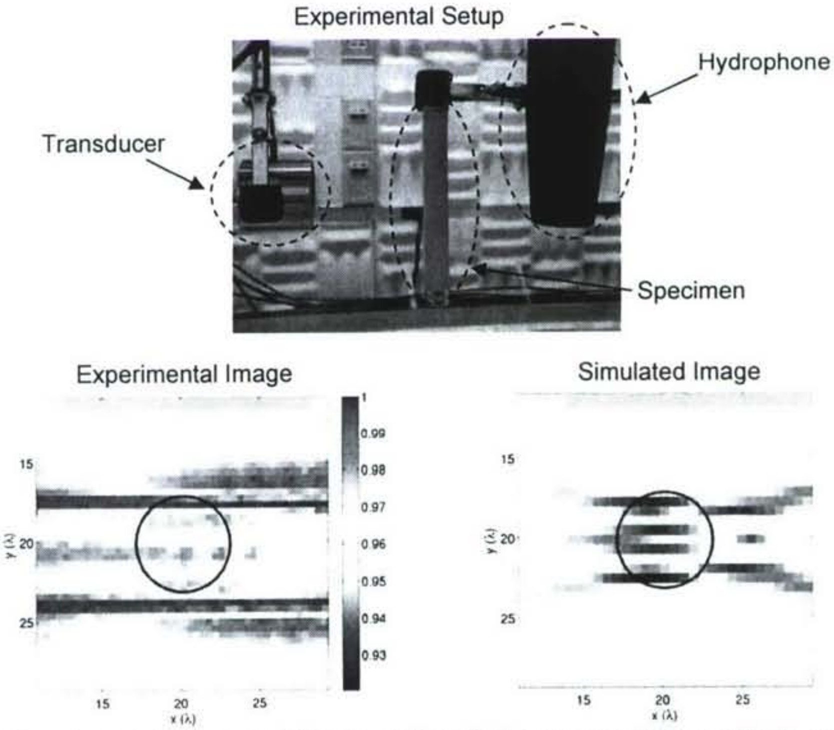
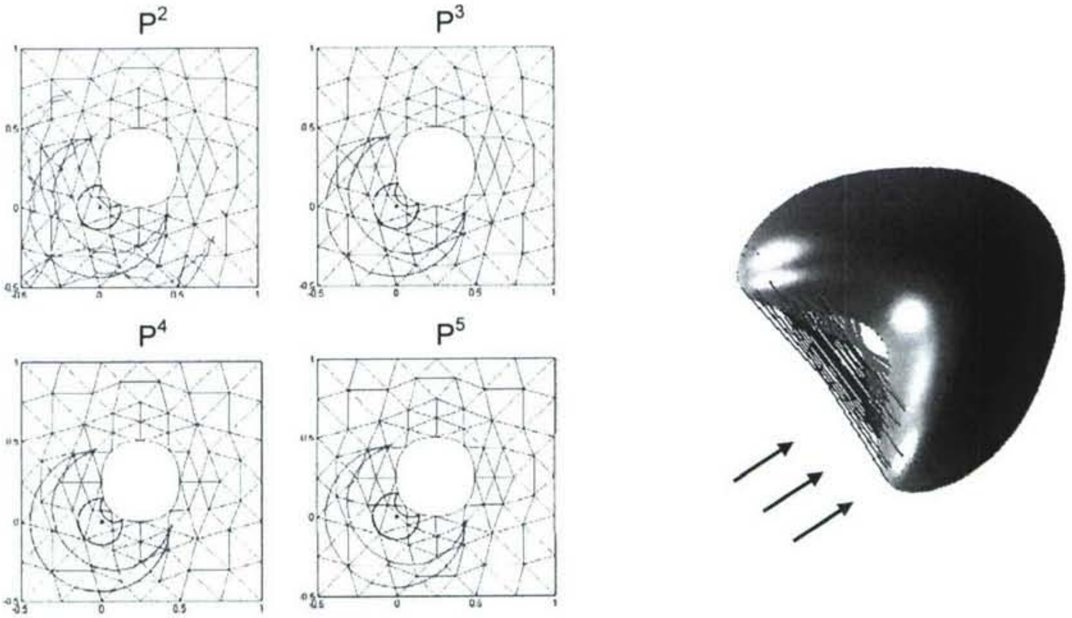


Figure 1. Experimental setup and image and preliminary numerical results for work on vibro-acoustography.

Generally applicable solution strategies, such as those described above, for the integral-equation formulation of scattering problems at moderate frequencies are necessary, as we have explained, to allow for a uniformly efficient methodology based on our new high-frequency integral-equation solvers (which reduce to "classical" approximation methods as the frequency decreases). At the other end, our work on new procedures for the solution of the GO model has also been largely motivated by our high-frequency work, as our approach to the solution of the integral equations in this case relies, in part, on knowledge of the phase of the unknown surface currents as provided by the GO solution. In relation to the latter, our effort focused on the simultaneous development of two alternative techniques for its determination. Specifically, on the one hand, we have developed a spectral/discontinuous-Galerkin method for the evaluation of wave-fronts in "phase space" that allows for the accurate treatment of curved boundaries which, as we have demonstrated, requires the use of specialized curved elements; see Figure 2(a). On the other hand, our work on an alternative spectral method based on "inverse ray-tracing" has resulted in two- and three-dimensional implementations that enable the treatment of complex geometries. A basic idea here relates to the use of fixed grids on the *receiving* portion of surface, rather than on the *emitting* part as done in classical ray tracing, and on the use of partitions of unity to permit the use of spectral interpolation schemes; see Figure 2(b).



(a) (b)

Figure 2. (a) p-convergence history for a sample scattering calculation using an isoparametric implementation of a spectral/discontinuous Galerkin method for the solution of the GO equations in phase space. (b) first reflections for a sample scattering calculation using the spectral "inverse ray-tracing" method (red and blue rays correspond to different −continuous− branches of the multi-valued phase).

Finally, again, a significant portion of our efforts has been devoted to the most ambitious part of our program relating to the design of rigorous solvers for *high-frequency* scattering applications. Significant accomplishments were attained in both **(i)** the implementation of a new, simple scheme for the simulation of three-dimensional rough-surface scattering at high-frequencies that greatly improves on the classical KA, at a very modest additional cost; and **(ii)** the design of a more complex high-frequency scattering code for the treatment of general bounded geometries that rigorously accounts for every effect, including shadowing and multiple scattering. Specifically, in relation with the effort **(i)**, advances include: **(1)** the development of high-order asymptotic procedures for the solution of the full electromagnetic problem at high frequencies in three space dimensions. The algorithms rely on high-order expansions of the surface current in powers of the wavelength and on the recursive evaluation of the coefficients through formulas derived from explicit asymptotic expansions of the integral equation that defines it; **(2)** the development of a high-order scheme to deal with surfaces that present multi-scale roughness. This procedure is based on the integration of high-order boundary-variation methods (developed under a previous AFOSR contract) with the high-order high-frequency rough-surface solvers that result from **(1)**. The former allow for the reduction of the overall problem to a sequence of problems with high-frequency incidence on a slowly varying surface (the smooth part of the original surface) which the latter are well-suited to resolve. In addition, significant progress has been made towards **(3)** the design and implementation of a more generally applicable rough-surface scattering algorithm based on the ideas that were initially advanced in connection with **(ii)** above. In contrast with the algorithms of **(i)** (where all integrations are performed analytically), these rough-surface schemes rely on the evaluation of the quasi-periodic Green's function (e.g. to apply suitable quadratures) whose calculation is particularly challenging at high frequencies. Thus, a significant portion of our efforts focused on the development of efficient and accurate procedures to effect these evaluations. As a result, a new technique has emerged which can be shown to outperform the state-of-the-art methodologies that are currently available to this end.

The main focus of our work in connection with **(ii)** above, on the other hand, has been on the design, analysis and implementation of the approach in the context of scattering by two- and three-dimensional bounded obstacles. As we mentioned, the methods are based on ideas of phase extraction, localized integration, full resolution of shadowing transitions and iterative account of multiple scattering effects. Advances in this connection include: **(4)** complete implementations for the treatment of single-scattering configurations in two and three dimensions (see Figure 3); **(5)** the realization of initial codes for the iterative evaluation of multiple scattering effects that incorporate phase information as derived from the GO solvers developed under this contract and described above; **(6)** a complete analysis of the convergence of the multiple scattering iterations for both scalar and vector models in two and three space dimensions. In particular, for instance, we have demonstrated that the convergence at high frequencies is *uniform* and determined solely by the geometry of interacting sub-scatterers (in fact, as we have found, the rate depends only upon the minimum distance among them and the curvatures and relative rotation of the principal axes of curvature at the points that minimize this distance). The relevance of this analysis goes beyond the theoretical as it enables some simple procedures to accelerate the convergence of the multiple-scattering iterations. Moreover, we have also shown that this convergence can be further accelerated through **(7)** the implementation of more sophisticated iterative linear solvers to account for higher-order reflections, and/or through **(8)** the development of suitable preconditioning schemes, e.g. based on approximate inverses calculated via the iterated KA. Finally, we have also realized **(9)** the design of entirely new and simplified approaches to both single- and multiple-scattering calculations. For the former, the new implementation is still based on the solution of the integral formulation of the scattering problem, but it relies on high-order high-frequency expansions (such as those described under **(i)** above) to deal with the scatter off illuminated regions, and on suitable mesh refinements and direct integration to capture the effects of shadowing transitions. For multiple-scattering evaluations, in turn, the new approach bypasses the need for iterative resolution of successive reflections as it allows for their simultaneous determination based on knowledge of the entire (multi-valued) GO solution. More precisely, the basic idea here is to use a simple collocation procedure to determine the slowly varying envelopes in a representation of the current as a sum of known, rapidly oscillatory exponentials (with phases derived from the GO model) modulated by unknown, smooth amplitudes.

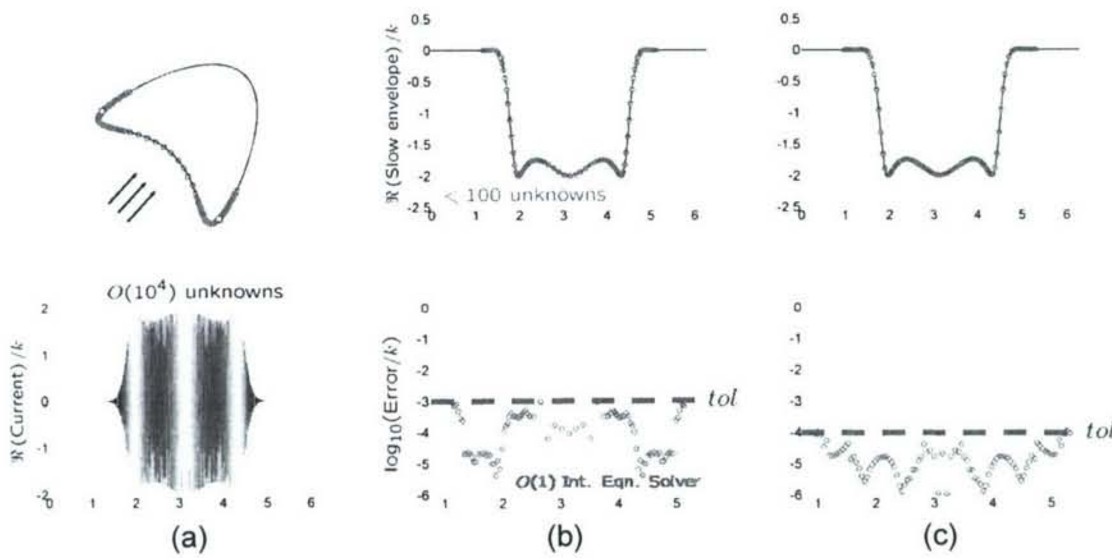


Figure 3. Sample high-frequency calculation for an obstacle with perimeter-to-wavelength ratio of approximately 900, showing error-controllability. (a) Configuration and full numerical solution (surface current); (b) Top: slow envelope for the current, numerical solution and errors for a tolerance of 10^{-3}; (c) Same as (b), with a tolerance of 10^{-4}.

PERSONNEL SUPPORTED/COLLABORATORS

- *Graduate Students (SUPPORTED BY THIS GRANT)*
  - Jiaqi Yang (School of Mathematics, University of Minnesota)
  - Harun Kurkcu (School of Mathematics, University of Minnesota).
  - Fanbin Bu (School of Mathematics, University of Minnesota).
  - Fatih Ecevit (Ph.D. 2005, Max Planck Institute for Mathematics in the Sciences, Leipzig, Germany).

- *Graduate Students (NOT SUPPORTED BY THIS GRANT)*
  - Akash Anand (Ph. D. 2006, Applied and Computational Mathematics, Caltech).
  - Catalin Turc (Ph.D. 2005, Department of Mathematics, University of North Carolina, Charlotte).
  - Deepa Gupta (School of Mathematics, University of Minnesota).
  - Yun Liu (School of Mathematics, University of Minnesota).

- *Post-Docs (NOT SUPPORTED BY THIS GRANT)*
  - Yassine Boubendir (Department of Mathematics, New Jersey Institute of Technology).
  - Qunsheng Cao (College of Information Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing, China).
  - Chiu-Yen Kao (Department of Mathematics, Ohio State University).
  - Alison Malcolm (Earth, Atmospheric and Planetary Sciences, MIT).
  - Jianliang Qian (Department of Mathematics, Wichita State University).
  - Jing Wang (Vital Images Inc.)

- *Faculty/Industrial Collaborators (NOT SUPPORTED BY THIS GRANT)*
  - Aria Abubakar (Schlumberger Doll Research).
  - Oscar Bruno (Applied Mathematics, California Institute of Technology).
  - Bernardo Cockburn (School of Mathematics, University of Minnesota).
  - Mostafa Fatemi (Ultrasound Research Laboratory, Mayo Clinic).
  - Christophe Geuzaine (Department of Electrical Engineering and Computer Science, University of Liège, Belgium).
  - James Greenleaf (Ultrasound Research Laboratory, Mayo Clinic).
  - Tarek Habashy (Schlumberger Doll Research).
  - David Nicholls (Department of Mathematics, University of Illinois at Chicago).

PUBLICATIONS

- *SUBMITTED*
  - Journals

[1] F. Ecevit and F. Reitich, "Analysis of multiple scattering iterations for high-frequency scattering problems. I: The two-dimensional case", submitted.

[2] A. Anand, Y. Boubendir, F. Ecevit and F. Reitich, "Analysis of multiple scattering iterations for high-frequency scattering problems. II: The three-dimensional scalar case", submitted.

[3] D. Nicholls and F. Reitich, "Boundary perturbation methods for high–frequency acoustic scattering", submitted.

- ACCEPTED
  - Journals

[1] Anand and F. Reitich, "An efficient high-order algorithm for scattering from penetrable thin structures in three dimensions", *J. Acoust. Soc. Amer.* **121** (2007), 2503-2514.

[2] Q. Cao, R. Kanapady and F. Reitich, "High-Order Runge-Kutta Multiresolution Time Domain Methods for Computational Electromagnetics", *IEEE Trans. Microwave Theory Tech.* **54** (2006), 3316-3326.

[3] F. Reitich and C. Turc, "High-order solutions of three-dimensional rough surface scattering problems at high-frequencies. I: the scalar case", *Waves in Random Media* **15** (2005), 1-16.

[4] F. Reitich and C. Turc, "High-order solutions of three-dimensional rough surface scattering problems at high-frequencies. II: the vector electromagnetic case", *Waves in Random Media* **15** (2005), 323-337.

[5] C. Geuzaine, O. P. Bruno and F. Reitich, "On the *O(1)* solution of multiple-scattering problems, *IEEE Trans. Magnetics* **41** (2005), 1488-1491.

[6] B. Cockburn, J. Qian, F. Reitich and J. Wang, "An efficient spectral/discontinuous finite-element formulation of a phase-space-based level set approach to geometrical optics", *J. Comput. Phys.* **208** (2005), 175-195.

[7] M.-H. Chen, B. Cockburn and F. Reitich, "High-Order RKDG Methods for Computational Electromagnetics", *J. Sci. Comput.* **22** (2005), 205-226.

- Book Chapters

[1] A. Malcolm, F. Reitich, J. Yang, M. Fatemi and J. Greenleaf, "Numerical modeling for assessment and design of ultrasound vibro-acoustography systems", in Vibrations and Acoustics in Biomedical Applications, Mostafa Fatemi and Ahmed Al-Jumaily, editors, ASME Press, to appear.

[2] O. P. Bruno and F. Reitich, "High order methods for high-frequency scattering applications", Lecture Notes in Computational Science and Engineering, H. Ammari, ed., Springer-Verlag, to appear.

- Conferences

[1] F. Ecevit and F. Reitich, "Decay of multiple-scattering iterates for trapping obstacles in the high-frequency regime. Proceedings of IABEM 2006, Graz, Austria, 2006.

[2] F. Ecevit and F. Reitich, "A high-frequency integral equation method for electromagnetic and acoustic scattering simulations: rate of convergence of multiple-scattering iterations", in *Proceedings of Waves 2005*, Providence, RI, 2005.

[3] F. Reitich and C. Turc, "High-order high-frequency solvers for rough-surface acoustic and electromagnetic scattering problems", in *Proceedings of Waves 2005*, Providence, RI, 2005.

[4] A. Malcolm, F. Reitich, Y. Yang, M. Fatemi and J. Greenleaf, "A complete computational model of ultrasound vibro-acoustography", Proceedings of IMECE2006, Chicago, IL, 2006.

[5] Y. Boubendir, F. Ecevit and F. Reitich, "Krylov subspace based acceleration strategies for the solution of high-frequency multiple scattering problems", Proceedings of Waves 2007, Reading, England, 2007.

[6] H. Kurkcu and F. Reitich, "Efficient calculation of Green's functions for the two-dimensional Helmholtz equation in periodic domains", Proceedings of Waves 2007, Reading, England, 2007.

INTERACTIONS/TRANSITIONS

- *Participation/Presentations At Meetings, Conferences, Seminars, etc*

    - Workshop on Computational High Frequency Waves, Wolfgang Pauli Institute, Vienna, Austria, 27 February 2007.
    - 23rd Annual GAMM Seminar, Max Planck Institute for Mathematics in the Sciences, Leipzig, Germany, 26 January 2007.
    - AFOSR Contractors Meeting, San Antonio, January 9-11, 2007.
    - Symposium on Vibrations and Acoustics in Biomedical Engineering, ASME International Mechanical Engineering Congress and Exposition, IMECE 2006, Chicago, 9 November 2006.
    - AHPCRC Meeting, University of Minnesota, Minneapolis, 24 October 2006.
    - IMA Workshop on Negative Index Materials, Institute for Mathematics and its Applications, Minneapolis, October 2-4, 2006.
    - Mathematical Modeling in Industry - A Workshop for Graduate Students, Institute for Mathematics and its Applications, University of Minnesota, Minneapolis, August 9-18, 2006 (*Organizer*).
    - AHPCRC Meeting, Aberdeen, May 23, 2006.
    - Case Western Reserve University, Cleveland, April 28, 2006.
    - Advances in Computational Scattering, Banff International Research Station, Banff, Canada, February 18-23, 2006 (*Organizer*).
    - AFOSR Contractors Meeting, San Antonio, January 11-13, 2006.
    - Rensselaer Polytechnic Institute, Troy, November 21, 2005.
    - Rice University, Houston, October 31, 2005.
    - AHPCRC Meeting, University of Minnesota, Minneapolis, August 16, 2005.
    - Mathematical Modeling in Industry - A Workshop for Graduate Students, Institute for Mathematics and its Applications, University of Minnesota, August 1-10, 2005 (*Organizer*).
    - Minisymposium on Discontinuous Galerkin Methods, USNCCM8, Austin, July 27, 2005.
    - Minisymposium on Advances in Boundary Element Methods, USNCCM8, Austin, July 25, 2005.
    - AHPCRC Meeting, Army Research Labs, Adelphi, May 17, 2005.
    - Minisymposium on Computational Electromagnetics, Frontiers in Applied and Computational Mathematics, Newark, May 13, 2005.
    - AFOSR Contractors Meeting, San Antonio, January 4-7, 2005.
    - Minisymposium on Numerical and Theoretical Aspects of Free-Surface Ocean Dynamics, SIAM Conference on Analysis of Partial Differential Equations, Houston, December 6-8, 2004 (*Organizer*).
    - Army Research Laboratories, Adelphi, November 1, 2004.

- *Consultative And Advisory Functions To Other Laboratories And Agencies*

    - Portfolio Coordinator, Battlefield Environment Portfolio, Army High Performance Computing Research Center, ARL-University of Minnesota, 2005-2007.
    - Portfolio Coordinator, Computational Electromagnetics Portfolio, Army High Performance Computing Research Center, ARL-University of Minnesota, 2002-2005.
    - Review Panel for the "Focused Research Groups" (FRG) initiative, National Science Foundation, November 7-8, 2005.

- *Transitions*

    - A collaborative project is ongoing with scientists at Schlumberger-Doll Research (SDR) on the design and implementation of volumetric scattering codes, inspired by the developments recounted here, for use in relation to geophysical prospection. Our collaborators at SDR are Dr. Aria Abubakar and Dr. Tarek Habashy. *[Work with graduate student J. Yang —supported by this contract—]*

    - A collaborative project is ongoing with the Ultrasound Research Laboratory at the Mayo Clinic (Rochester, Minnesota). The objective of the effort is to develop efficient and accurate scattering solvers to aid in the development of "vibro-acoustography" (*Science* **280**, pp. 82-85, 1998). The transition is based on suitable extensions and applications of the numerical schemes developed under the present contract. Our collaborators at the Laboratory Dr. James Greenleaf and Dr. Mostafa Fatemi. *[Work with graduate students J. Yang and Fanbin Bu —supported by this contract—, and postdoctoral associate A. Malcolm —not supported by this contract—].*